Additive Manufacturing (AM) Activities & Non-Destructive Evaluation (NDE) at GSFC

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JAXA Delegation Visit
2/2/2017

NASA
Goddard Space Flight Center
Materials Engineering Branch

Presentation Outline

- NDE Lab Overview, highlighting CT capabilities
- Ongoing OSMA NDE Program Task Overview
  - Task 1: Develop image quality indicators for x-ray computed tomography (CT) similar to those used for traditional x-ray NDT to measure unsharpness, resolution, or contrast sensitivity.
  - Task 2: Probability of Detection (POD) study for flaws in AM parts. Assess various flaw types and material limitations, then generate flaw panels and perform round-robin POD using CT
- Overview of other related AM-related inspection activities at GSFC

NDE Lab Overview, highlighting CT capabilities

NASA
Goddard Space Flight Center
Materials Engineering Branch

Organization

- The Non-Destructive Evaluation (NDE) laboratory at GSFC is part of the Materials Engineering Branch/Code 541, which is part of the Mechanical Systems Division of the Engineering Directorate.
- The NDE Lab supports the quantitative and qualitative inspection of both metallic and nonmetallic spacecraft hardware for active flight projects.
- Beyond GSFC inspections, which typically fall under SMD, the NDE lab also provides work for the OSMA NDE Program and the NASA Engineering and Safety Center (NESC).
- GSFC NDE Personnel:
  - 4 Civil Servants (not all full time NDE)
  - 3 Contract Employees (not all full time NDE)
  - Plus a similar number of inspectors in SMA who certify lifting devices
  - Main POC: Justin Jones; justin.s.jones@nasa.gov

GSFC NDE Lab Capabilities

- **Radiography**
  - **X-ray Computed Tomography system**
    - Customized North Star Imaging X5000 system, up to 3 micron resolution (75 micron for large objects)
    - Source: Yxlon, model FXE-225.99, 225 kVp, Dual-Head Microfocus
    - Detector: Dexela 7529 CMOS panel w/75 µm pitch, 3888 x 3072 pixel resolution
    - 7-axis part manipulation capability
  - **Real Time X-ray system**
    - Source: Fein Focus, model FXT-225.20, 225 kVp, Microfocus
    - Detector: Varian PaxScan 2520V, AmSi panel w/127 µm pitch, 1516 x 1900 pixel resolution
    - 5-axis part manipulation capability
- **Infrared Thermography**
  - TWI EchoTherm lite flash IR system
  - FLIR SC8200 detector w/ 18µm pitch, 1024 x 1024 resolution, 3-5µm spectral range
- **Ultrasound**
  - Panametrics MULTISCAN Immersion scanning system
    - 72"L x 40"W x40"D tank
    - Motorized X, Y, Z, rotary and manual gimbal/swivel motion
  - Panametrics Epoch III portable/handheld system
  - Olympus Epoch 1000i portable/handheld system
  - NDT Systems Raptor/StringScan portable/handheld C-scan system
- **Eddy Current**
  - Zetec MIZ-21B portable system
- **Fluorescent Penetrant**
  - Methods: A, C, D

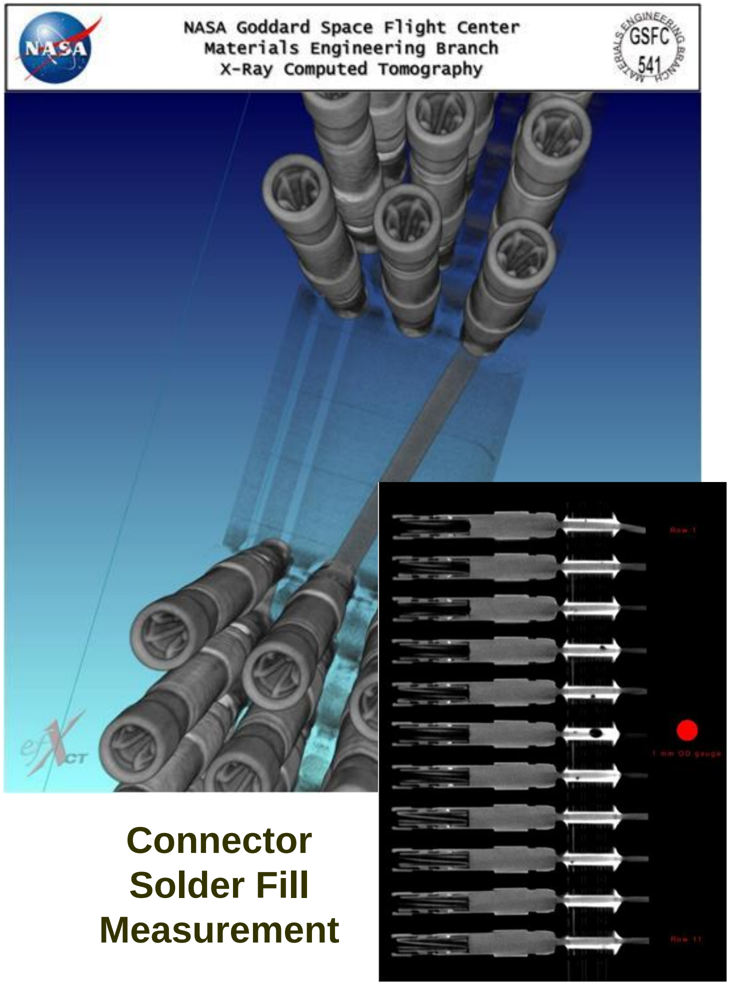
GSFC Code 541 X-Ray CT System

Capabilities

- Can operate in 2D or 3D mode (cone-beam CT)
- Large format CMOS detector for larger specimens or high magnification
- Greatly reduce need for high cost DPAs
- Automatic calibration software with report
- Ultra-fast GPU reconstruction (several minutes)
- Up to 3 μm resolution (127 μm for large objects)
- Density segmentation and surface extraction to CAD (reverse engineering)

Typical Applications

- Circuit board inspection (locate shorts, poor solder joints, thickness gauging, etc.)
- Composites analysis (joint inspection, flaw detection, lay-up verification)
- Metallic inspection (locate voids, inserts, cracks)



Connector Solder Fill Measurement

GSFC Code 541 X-Ray CT System

X-ray Source: Yxlon FXE-225.99 Dual Head, Microfocus

- Transmission head: 10 W, <2 µm spot size
- Directional head: 280 W, <6 µm spot size

Detectors:

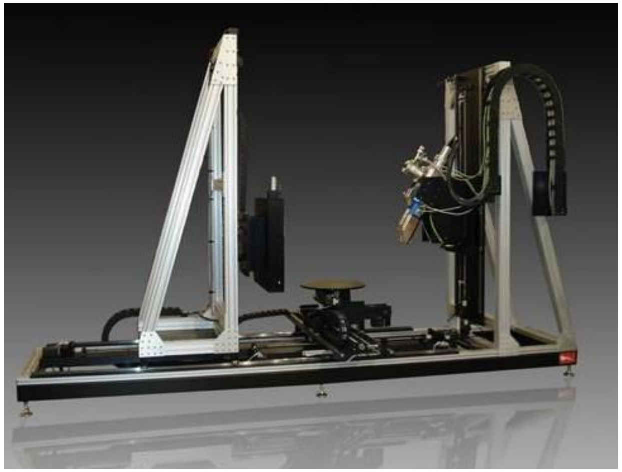
- Dexela 7529
  - CMOS array with CsI scintillator
  - 75 µm pitch, 3888 x 3072 pixel array
  - 14-bit and 26 FPS
  - 230 x 290 mm area detection
- Varian PaxScan 2520V
  - Amorphous Si with CsI scintillator
  - 127 µm pitch, 1516 x 1900 pixel array
  - 14-bit and 8 FPS
  - 193 x 242 mm area detection

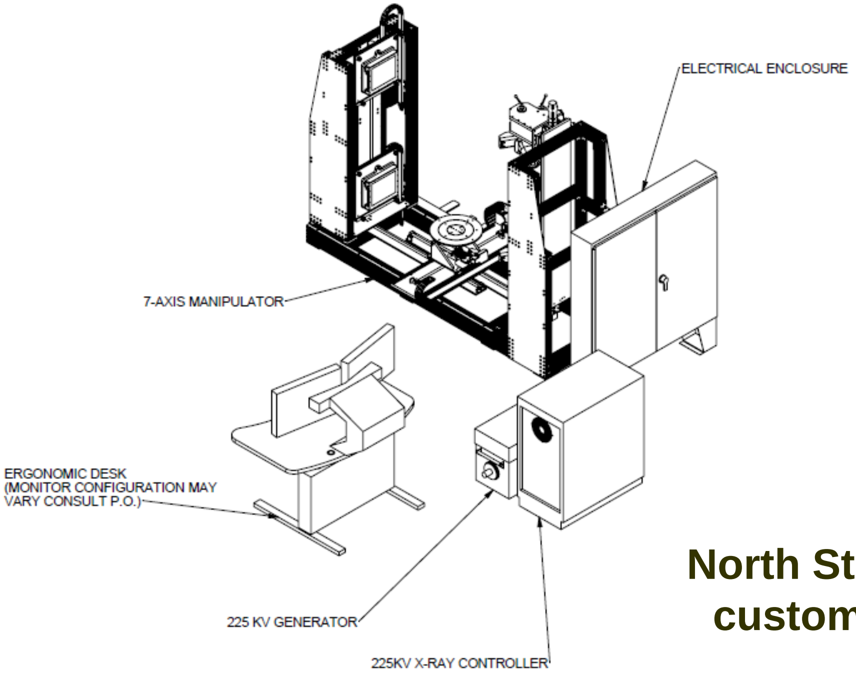
North Star Imaging, custom X5000CT

GSFC Code 541 X-Ray CT System

Other Components:

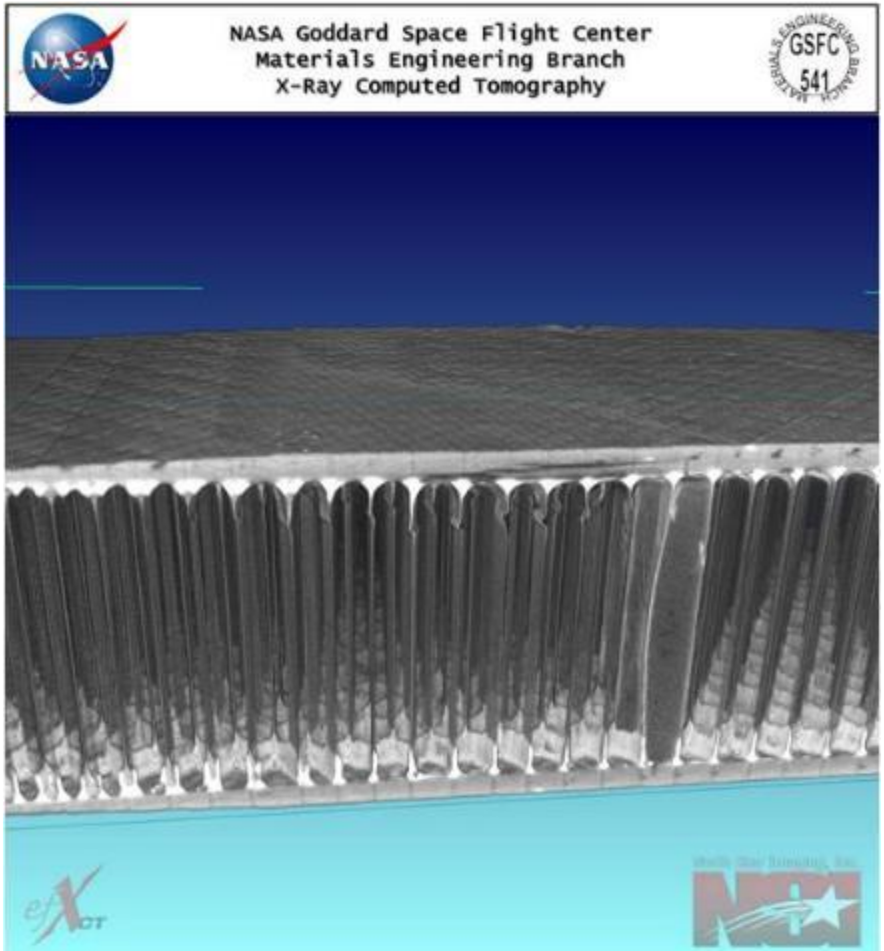
- 7-axis motion/manipulator system, up to 100lb capacity on rotation stage
- Installed in radiation shielded room
- North Star Imaging software
- Reconstruction PC with 4 Tesla GPU computing



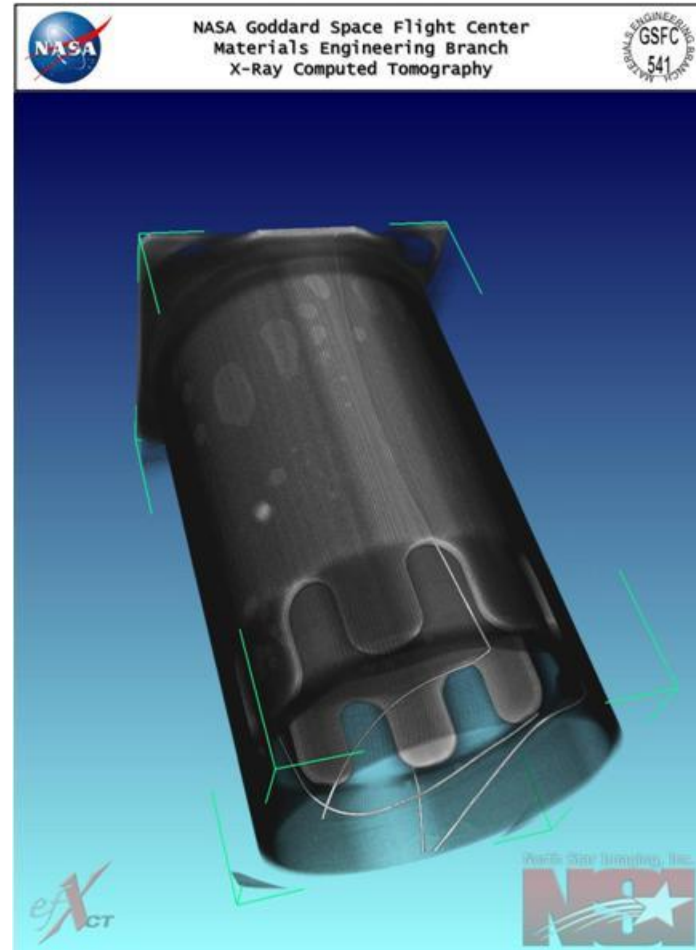


North Star Imaging, custom X5000CT

Examples - Composites

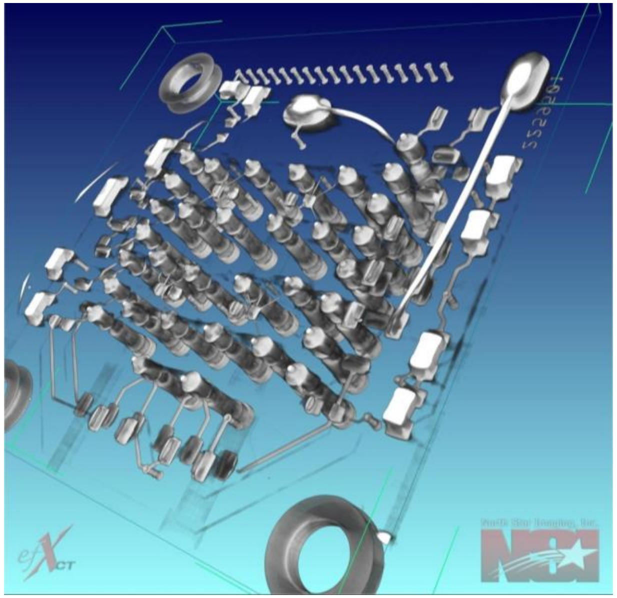


Impact Damage in Structural Composite



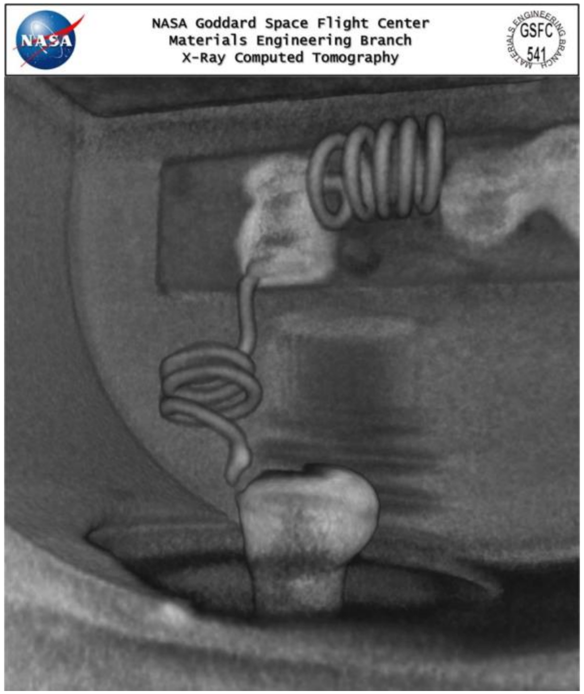
Epoxy Voids in Composite Boom End Fitting

Examples – Circuit Boards/Components



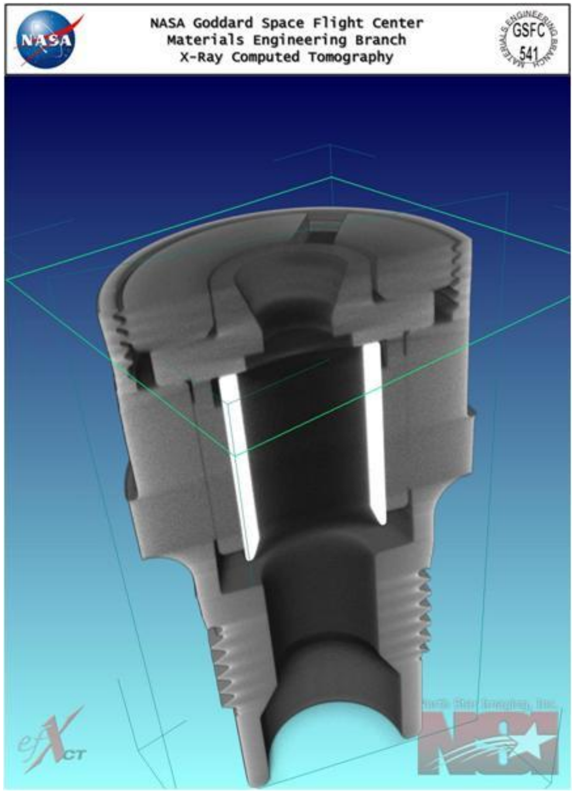
Full Circuit Board

Poor contact of coil in Electronic Resonator



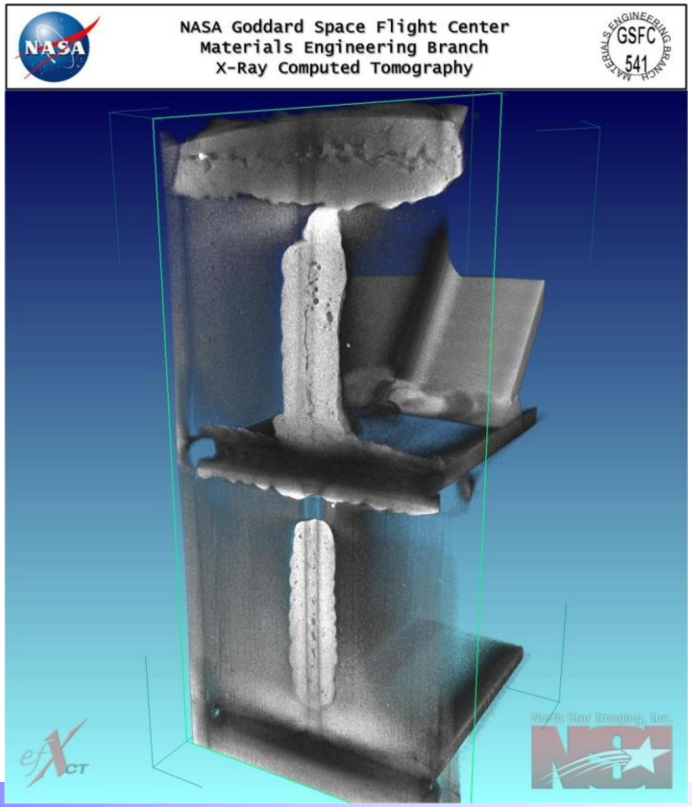
Diodes inside Circuit

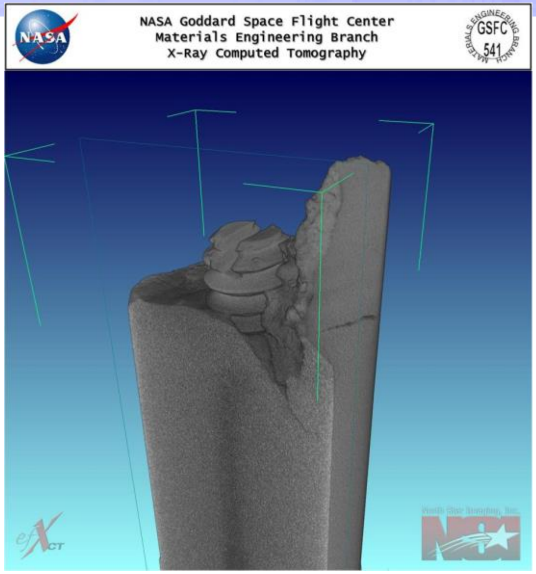
Examples – Metallic Parts



Compression Fitting

Porosity in 3D Welded Joint





Failed Damper Shaft
Crack Detection

OSMA NDE Program Task 1: Development of X-Ray Computed Tomography (CT) Inspection Standards

NASA
Goddard Space Flight Center
Materials Engineering Branch

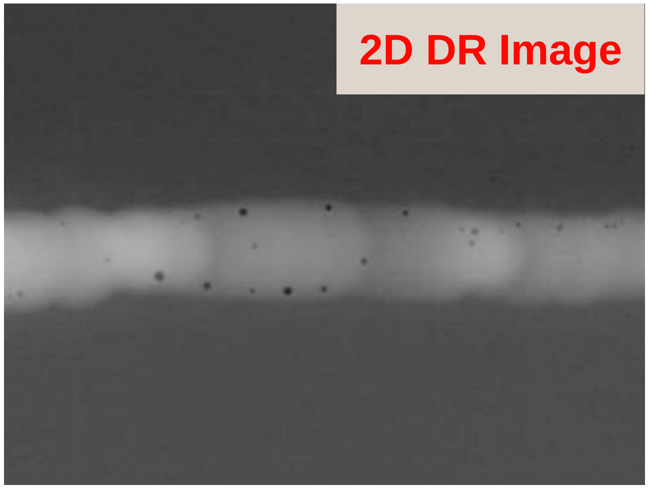
Task 1 Objectives

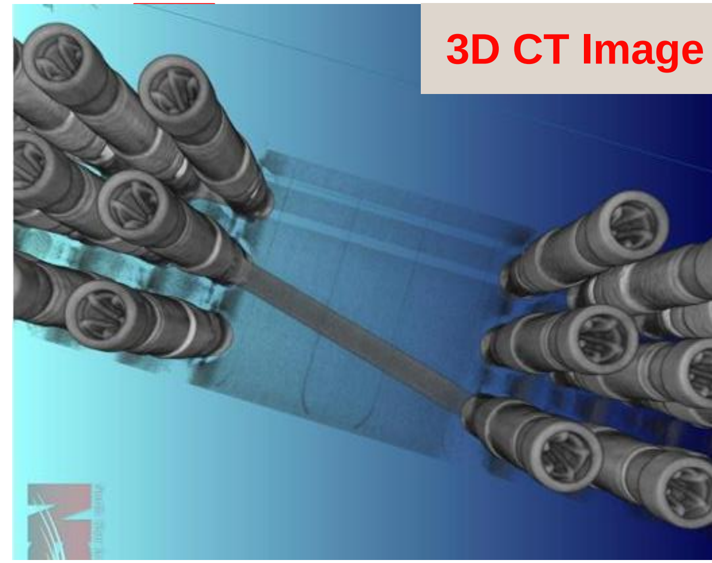
- Develop a set of tools to assess Computed Tomography (CT) system performance, similar to those used for traditional x-ray NDT to measure unsharpness, resolution, or contrast sensitivity. Currently there are no universally accepted or commercially available IQIs for CT
- Identify materials and design internal features useful for assessing inspection capabilities
- Fabricate Image Quality Indicators (IQIs) to simulate above features
- Analyze IQI volume data to assess CT detectability limits, contrast sensitivity, and resolution

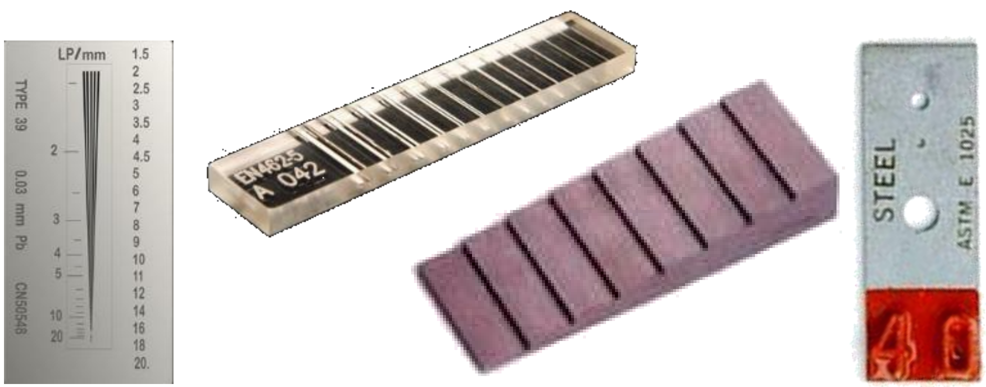
- *Reverse approach…*

  Use CT system to ascertain AM material build defects and limitations

Standard Image Quality Indicators



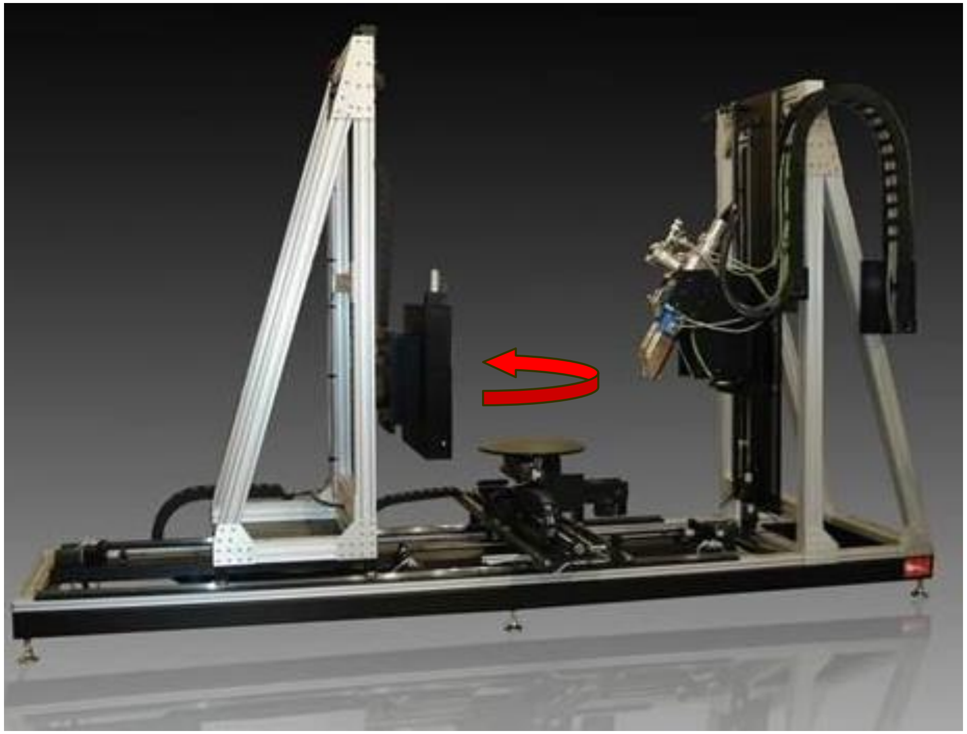




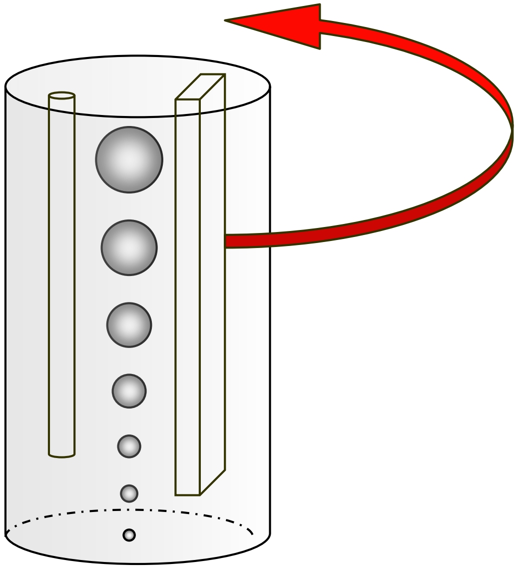
?

From left: Convergent line pair gauge, duplex line pair gauge, step block, plaque penetrameter [ndtsupply.com]

IQI Development Concept



CT system showing rotational axis. Since reconstruction is based on multiple viewing angles, we proposed using axial-symmetric standards to measure system performance.



IQIs conducive to CT
(rough concepts shown above: not actual designs).

AM Fabrication of Phase 1 X-ray CT IQIs

Material	PH1 Stainless Steel (15-5 analog)	Titanium 6Al-4V	Vero White Plus RGD835 (proprietary photopolymer)
Manufacturer	GPI Prototype and Manufacturing Services	GPI Prototype and Manufacturing Services	Alio Designs
Build Method	Direct Metal Laser Sintering	Direct Metal Laser Sintering	PolyJet
Layer Thickness (µm)	40	30	30
Minimum Feature (mm)	0.3	0.5	1.6

Assess x-Ray CT using AM IQIs

Assess AM IQIs using x-Ray CT

Assess Phase 1 AM IQIs using x-Ray CT

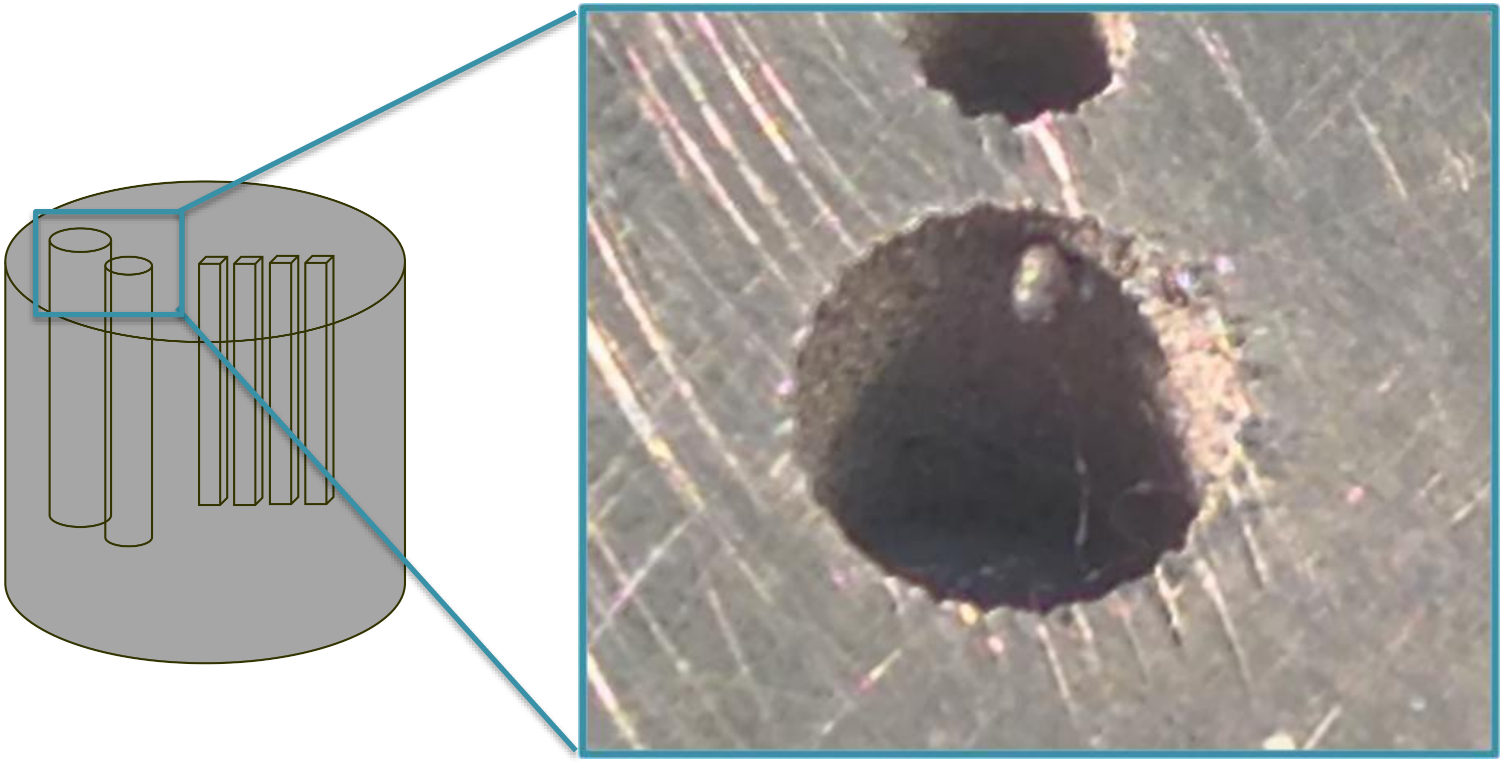
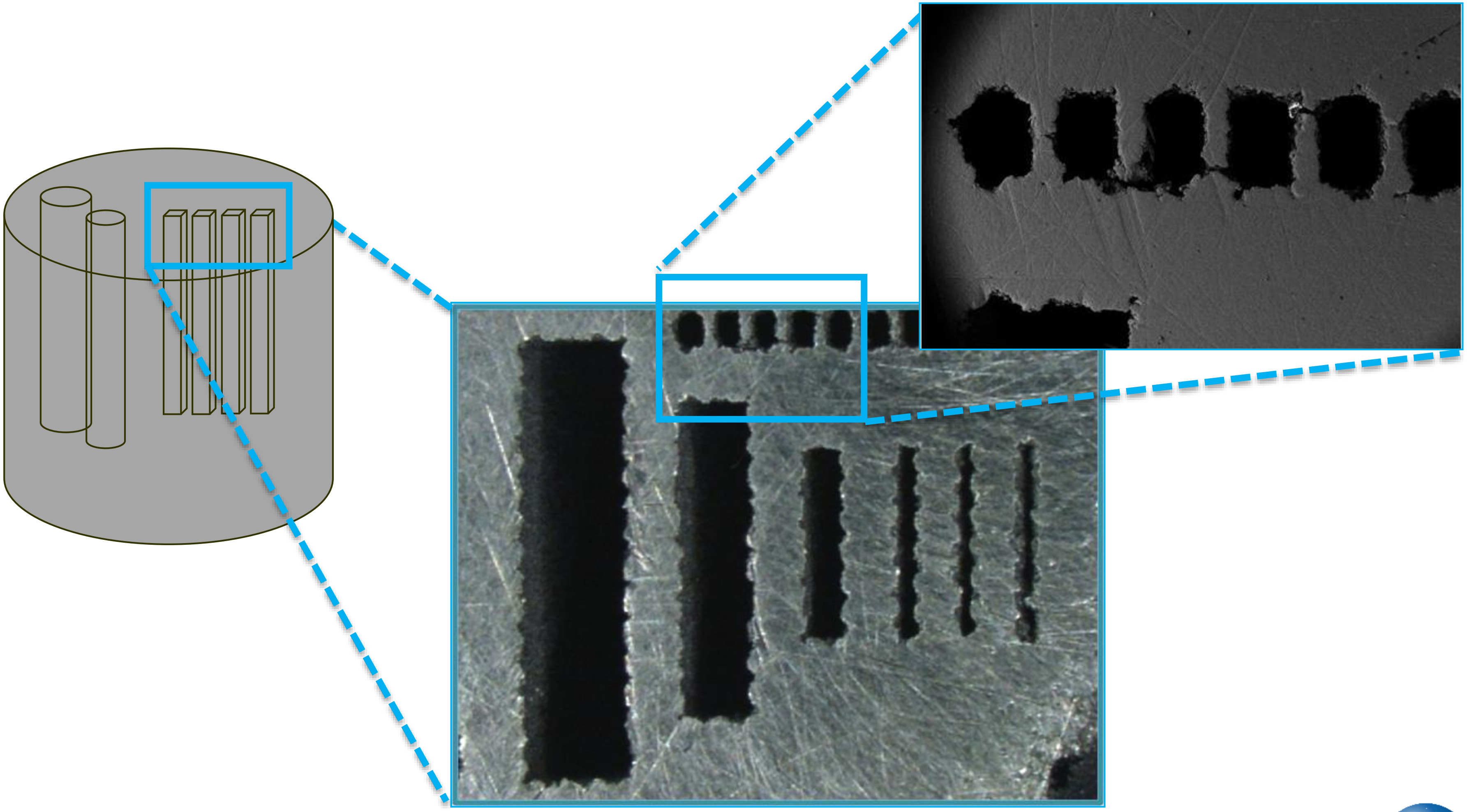


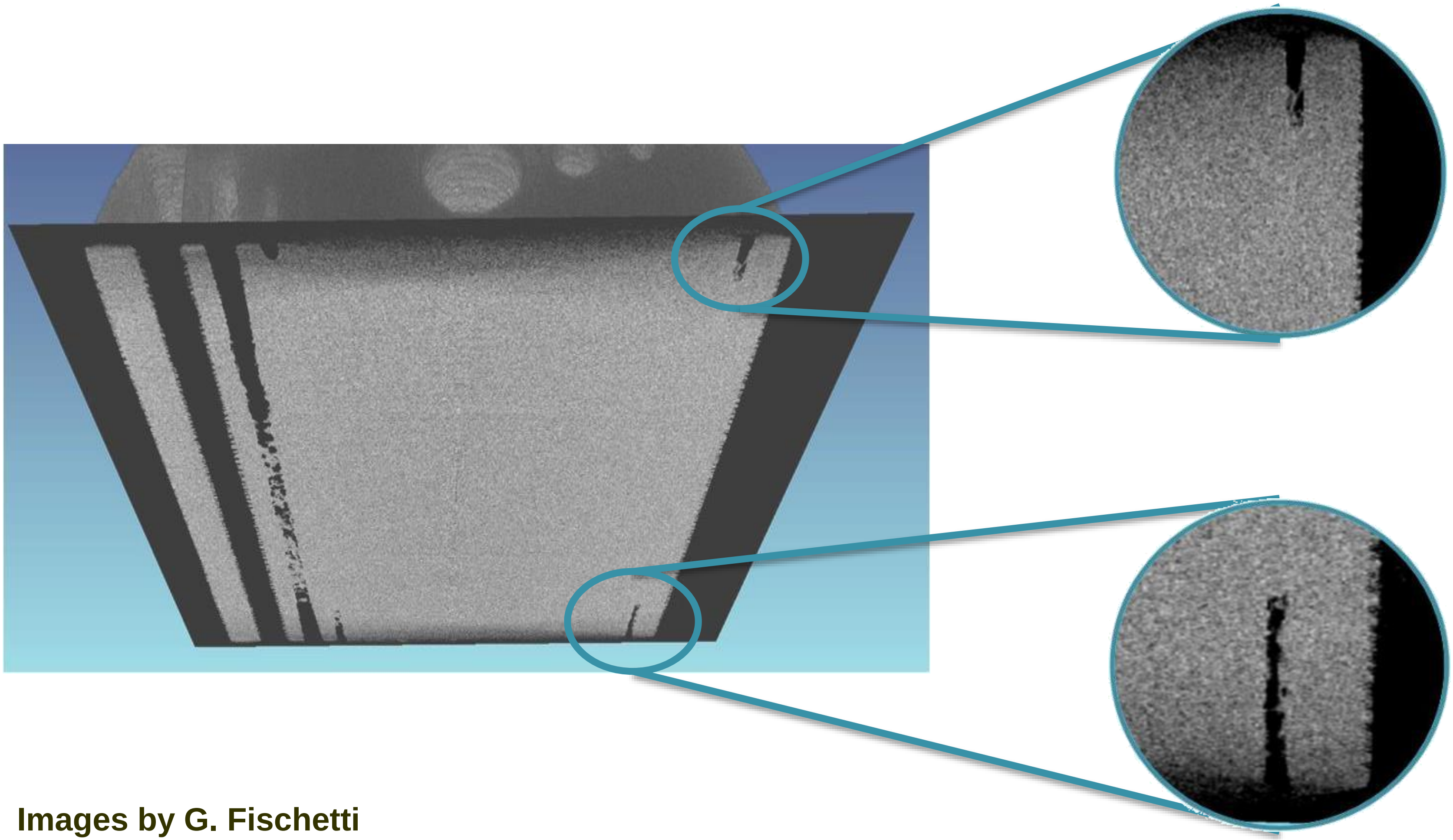
Image by G. Fischetti

Assess Phase 1 AM IQIs using x-Ray CT



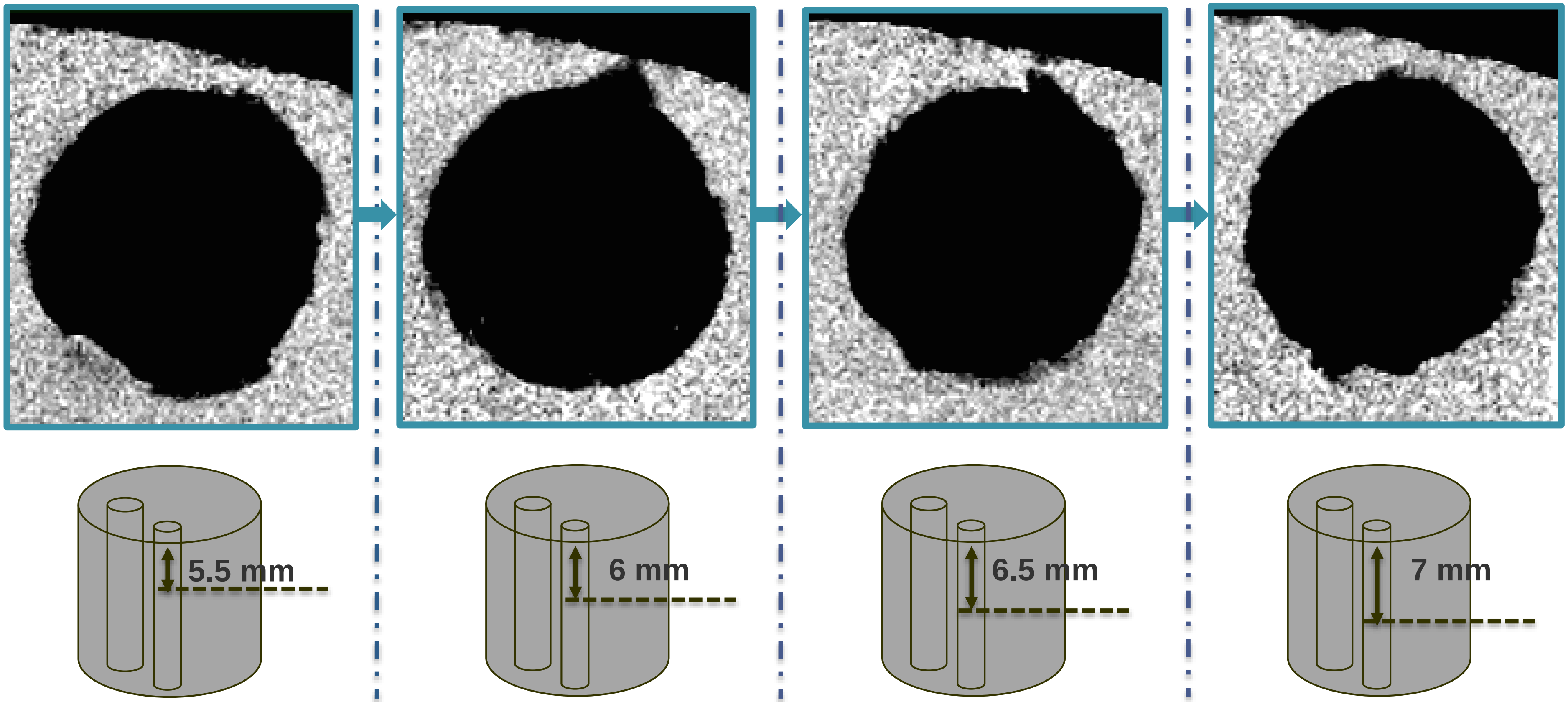
 Images by G. Fischetti

Assess Phase 1 AM IQIs using x-Ray CT



Images by G. Fischetti

Assess Phase 1 AM IQIs using x-Ray CT



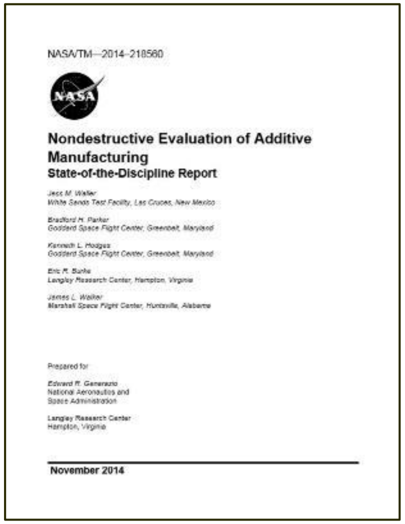
Images by G. Fischetti

OSMA NDE Program Task 2: X-ray CT Detectability of AM Parts via Point Estimate/POD

NASA
Goddard Space Flight Center
Materials Engineering Branch

Motivation

- Key findings from NASA’s "Nondestructive Evaluation of Additive Manufacturing State of the Discipline Report" (2014):
  - For AM parts, inherent complexity drives the need for advanced NDE by x-ray Computed Tomography (CT).
  - CT is considered to have the greatest potential based on its unique ability to provide quantitative 3-dimensional data across a wide range of materials, dimensions, and shapes.
    - Fabrication of physical reference standards is needed to verify and validate CT NDE data.
- Probability of Detection (POD) data does not exist for common AM flaw types.
  - Crucial to establishing inspection limitations for CT.



NASA/TM—2014–218560

Nondestructive Evaluation of Additive Manufacturing
State-of-the-Discipline Report

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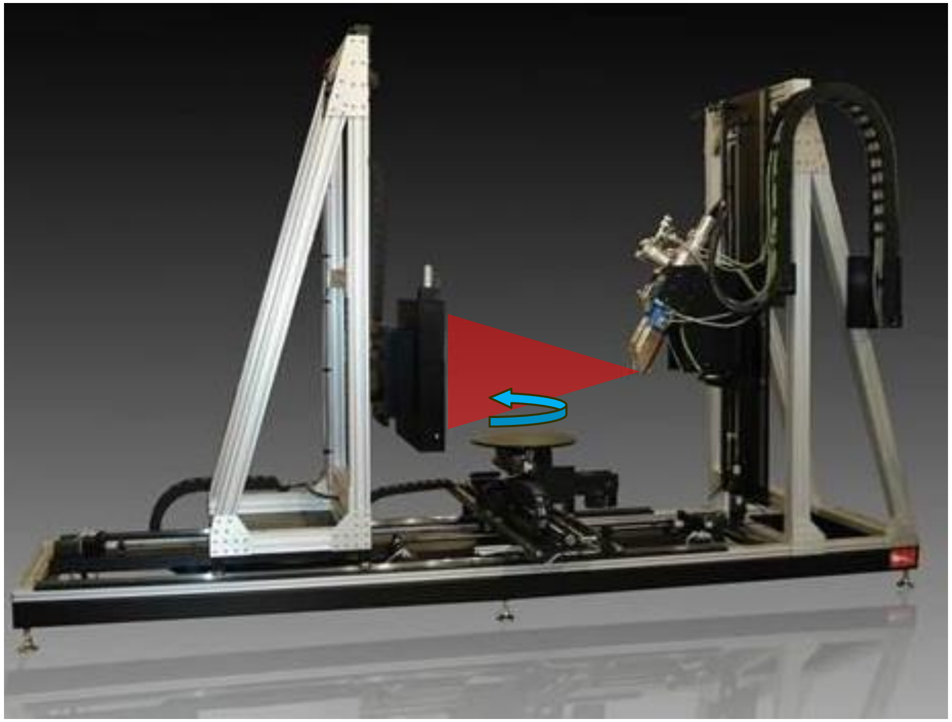
November 2014

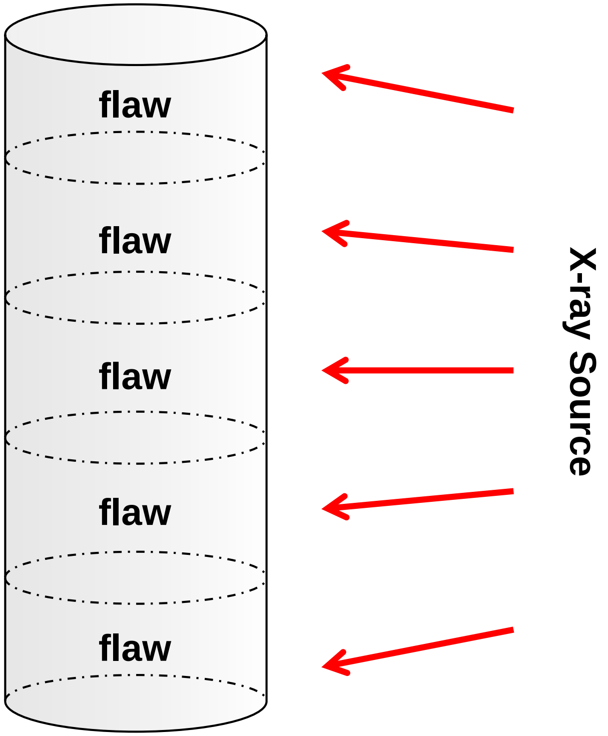
Task Objectives

- Identify common AM flaw types (i.e., shapes, sizes, locations, materials, applications, etc.)
- Work with partners LaRC, JSC and MSFC to design flaw specimens
  - Want to build off defect detection work being done at MSFC to pick defect types and flaw sizes relative to SLS applications.
- Identify vendors to fabricate seeded flaw specimens
- Round-robin inspections on produced flaw specimens
- Perform probability of detection (POD) analysis to assess CT system performance for select AM - produced flaws
  - Utilize data from "round-robin" inspections

Flaw Specimen Development

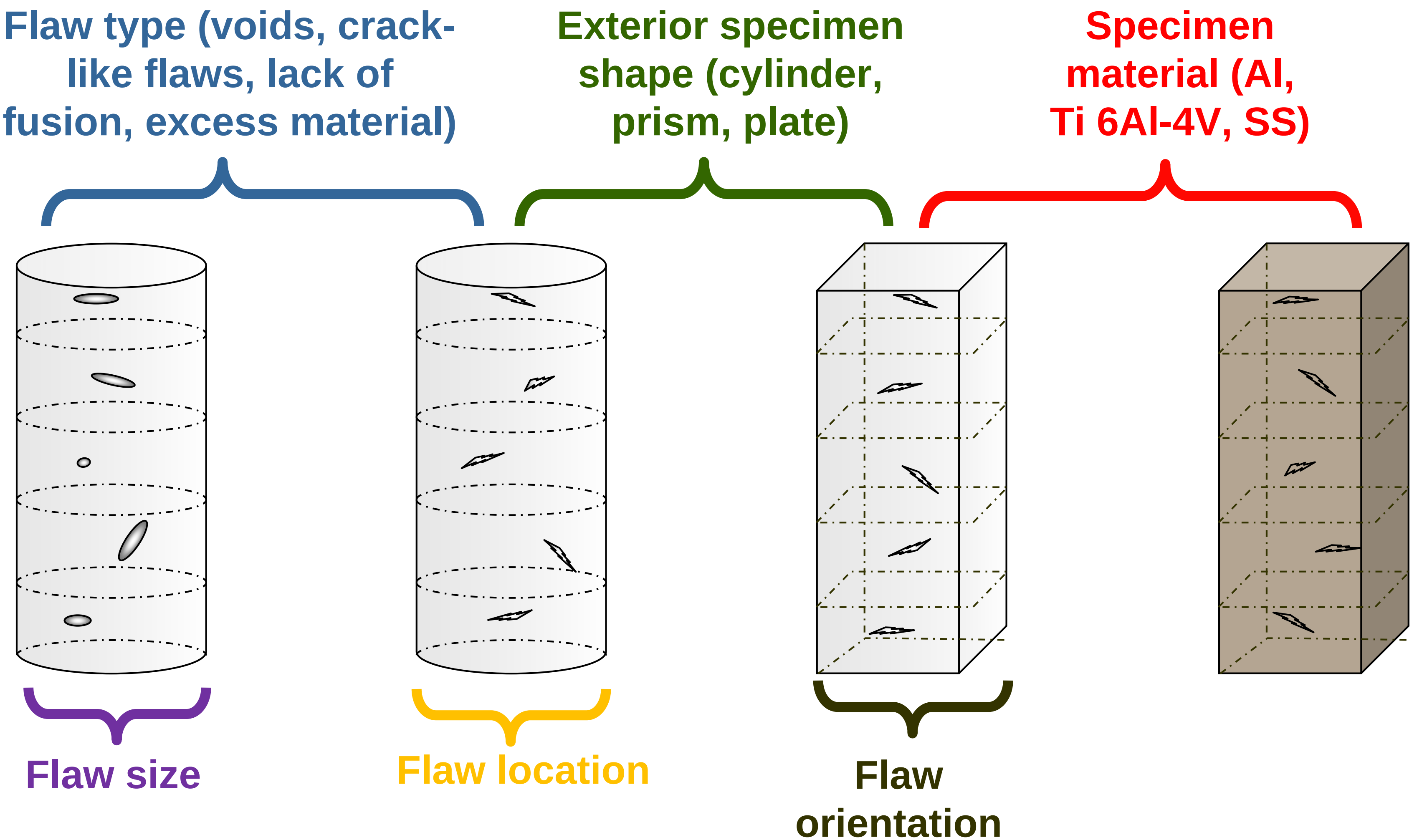


CT system showing rotational axis and cone beam.



- Flaw standard(s) will incorporate a “stack” of flaws embedded into a compound, net-shape AM part to reduce fabrication costs
- If flaws spaced sufficiently apart, roughly parallel nature of x-ray beam permits independent inspection of each flaw

Design of Experiments: Iterating Flaw Specimen Design Variables



A Few Related AM Activities within the Materials Branch (Code 541) and Across GSFC

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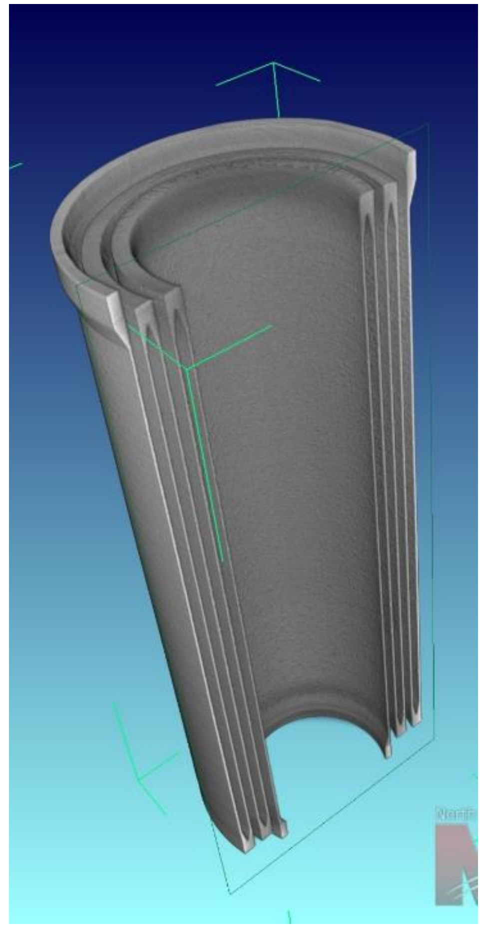
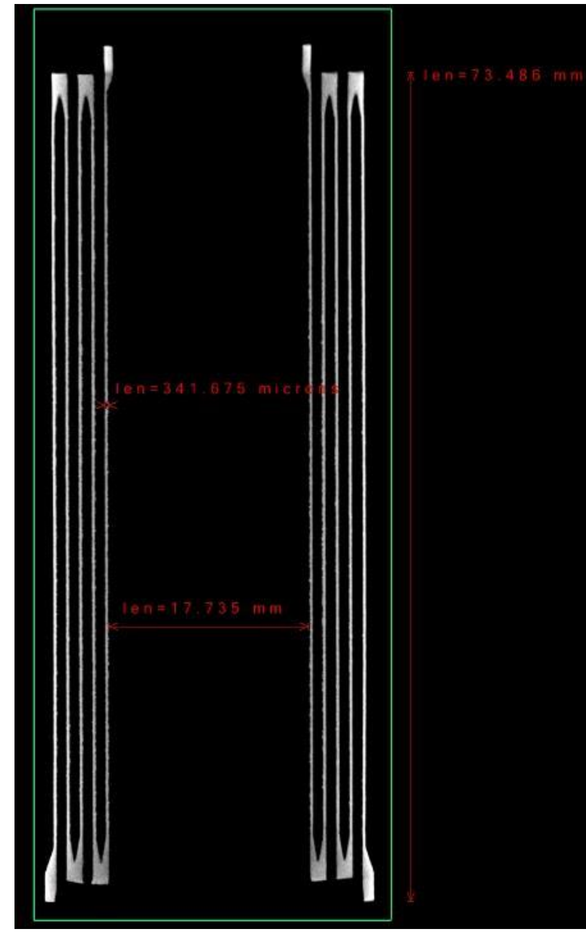
Goddard Space Flight Center
Materials Engineering Branch

541 Case Study 1: CT inspection of Cryogenic Adiabatic "Heat Switch" Body

Additively Manufactured (AM) 5-Shell
Re-Entrant Heat Switch



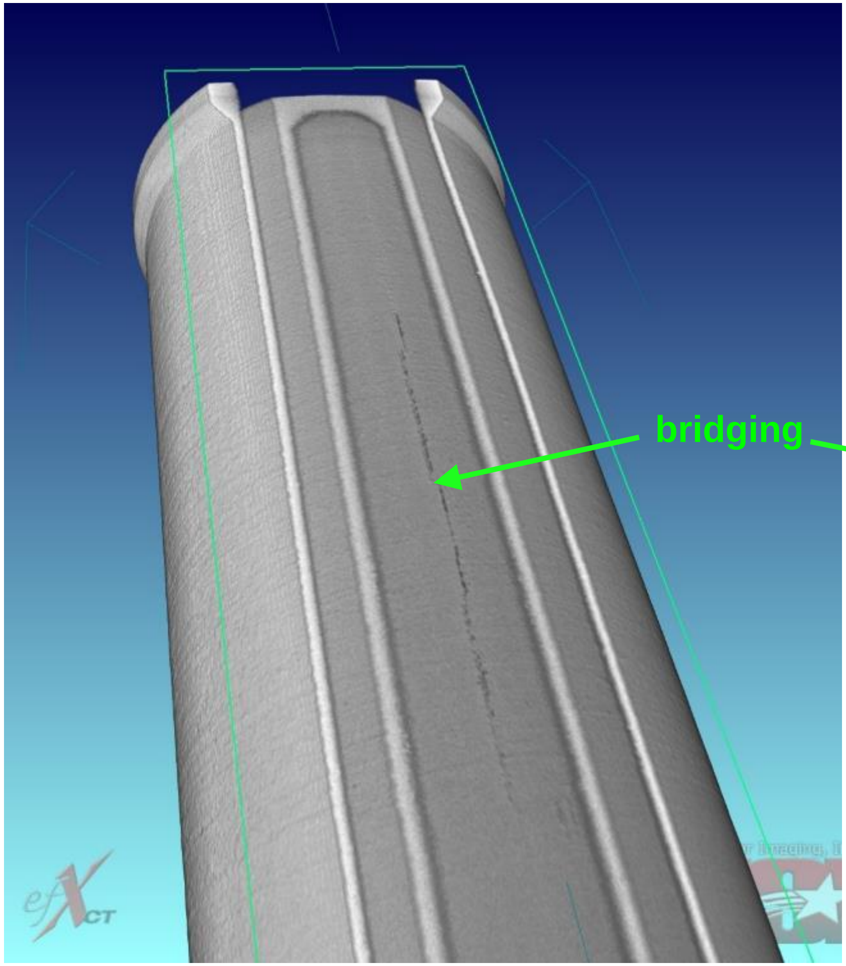


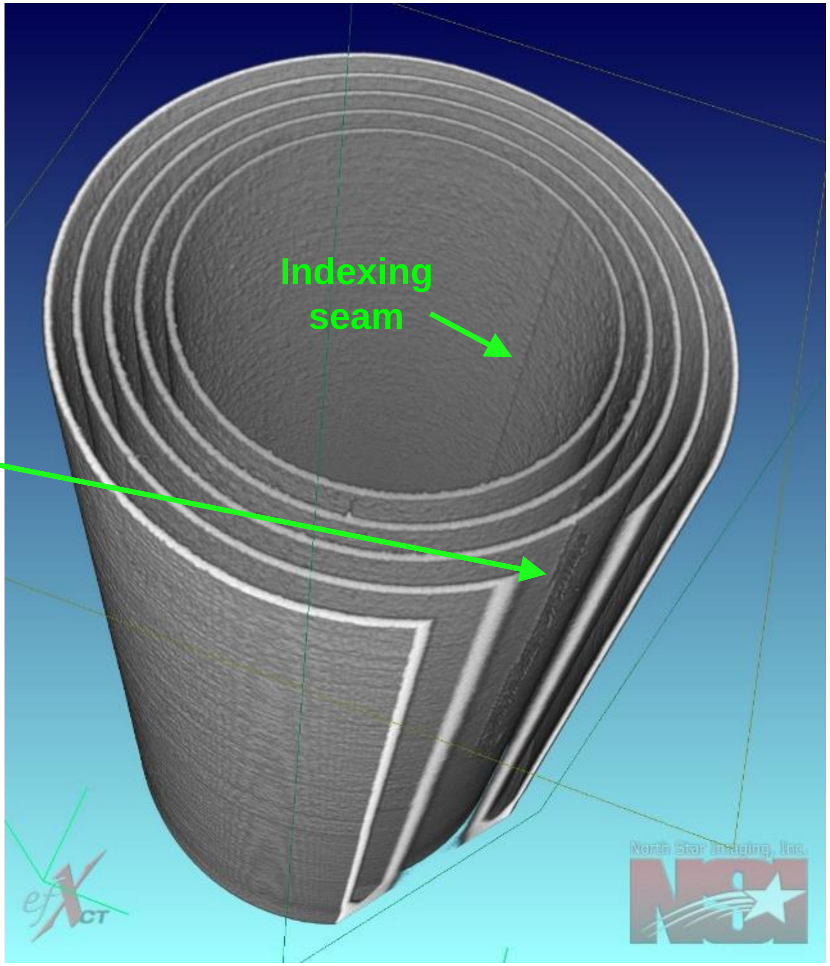
Inspection Criteria from project:

- *Tube walls must be uniform, with minimal fabrication defects*
- *Voids (helium loss) or bridging (thermal conduits) may be cause for rejection*

Project P.I. information available upon request.

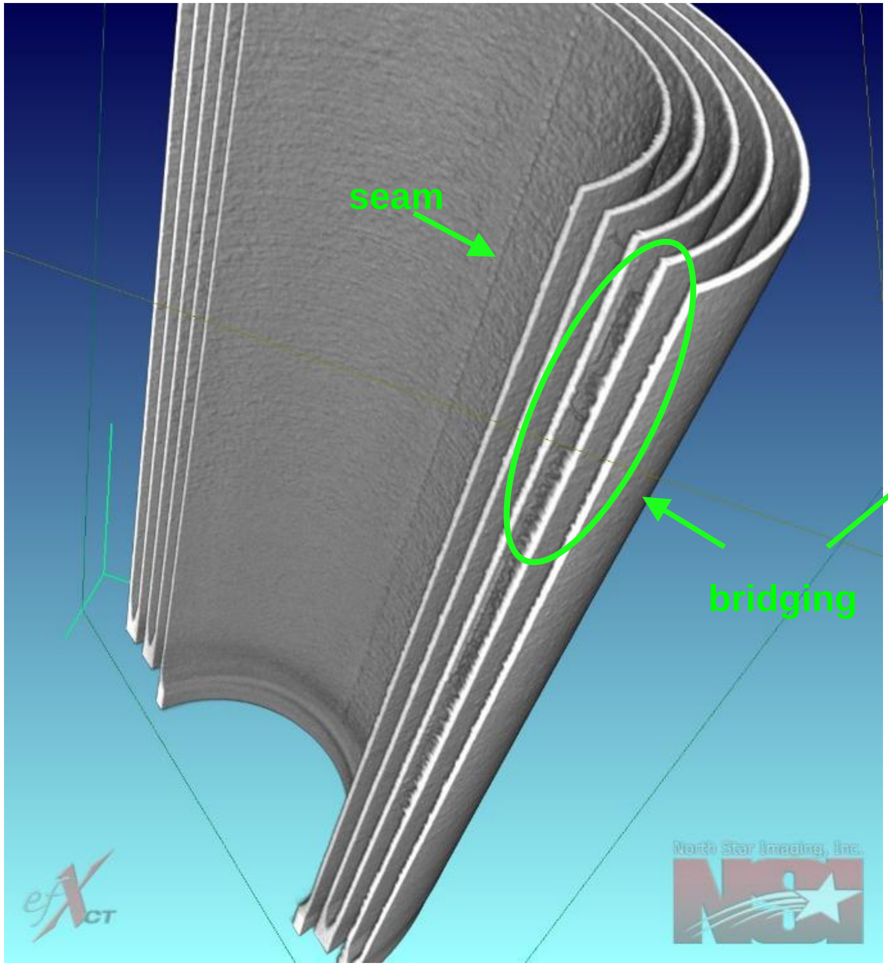
541 Case Study 1: CT inspection of Cryogenic Adiabatic "Heat Switch" Body

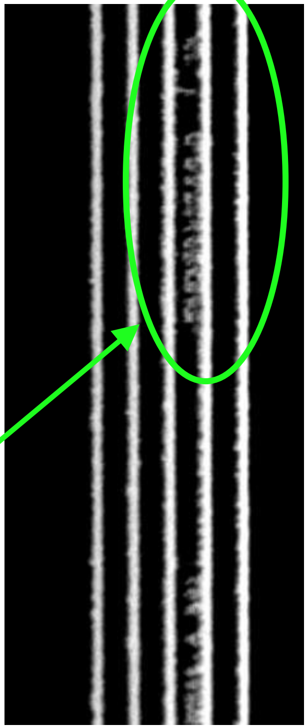




Project P.I. information available upon request.

Case Study 1: CT inspection of Cryogenic Adiabatic "Heat Switch" Body for Astro-H

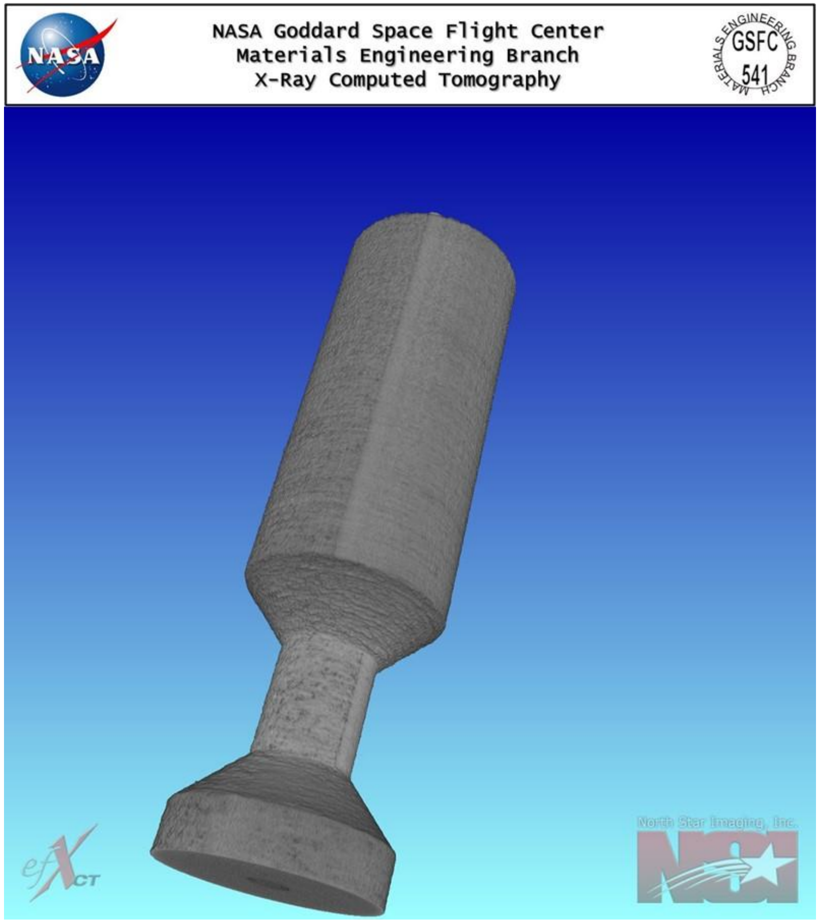


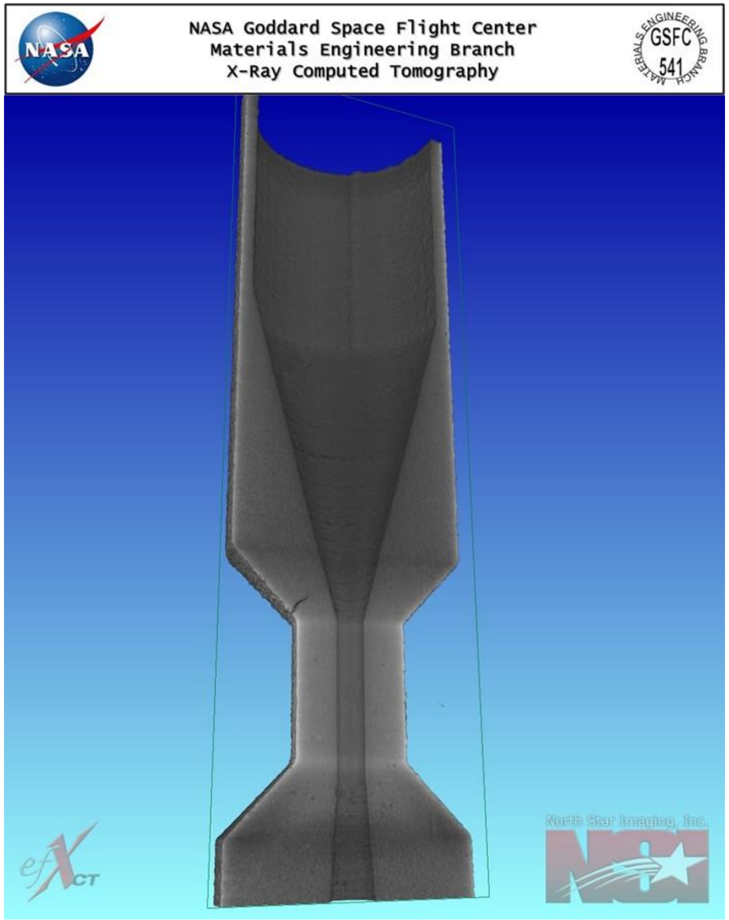


- These flaws were found relatively easy with CT and the Pass/Fail requirement was clear.
- But what if the Program's Pass/Fail criterion is not so binary and flaws of a certain size need detected?

Project P.I. information available upon request.

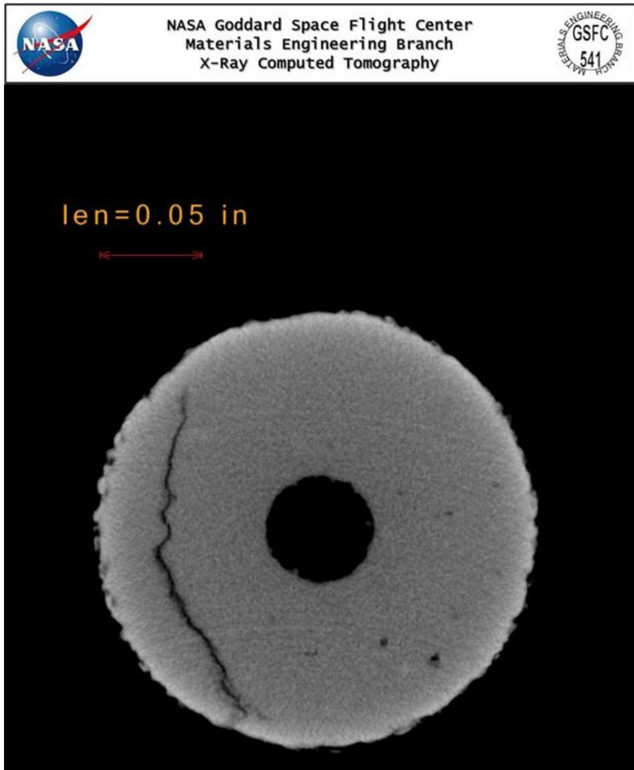
Case Study 2: CT inspection of AM Venturi Tube

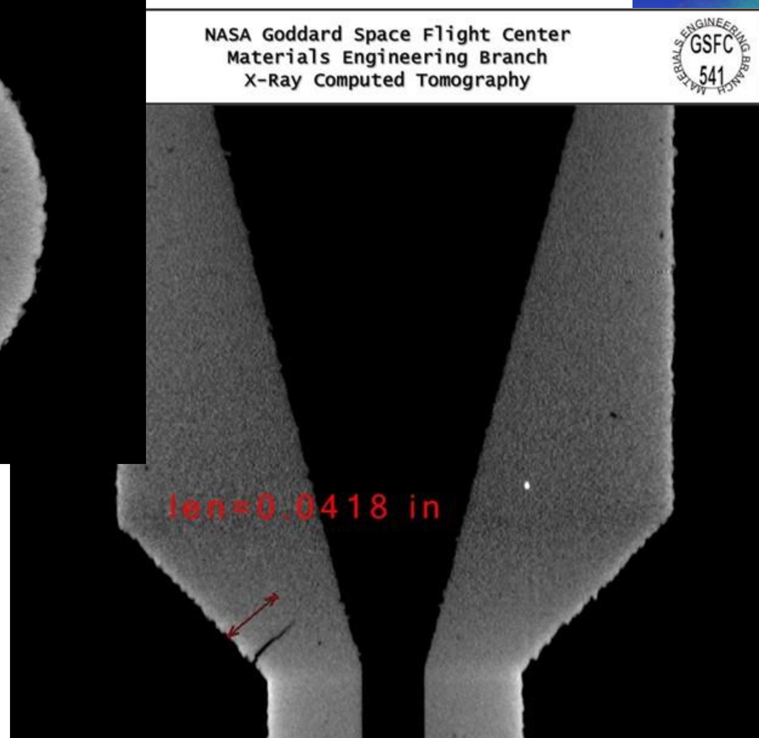


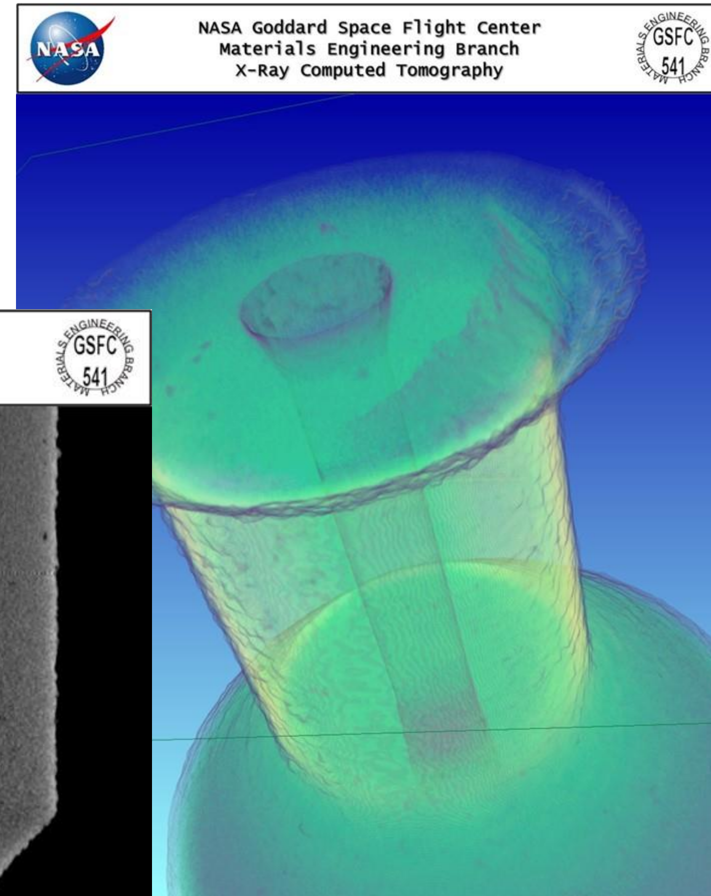


Project P.I. information available upon request.

Case Study 2: CT inspection of AM Venturi Tube



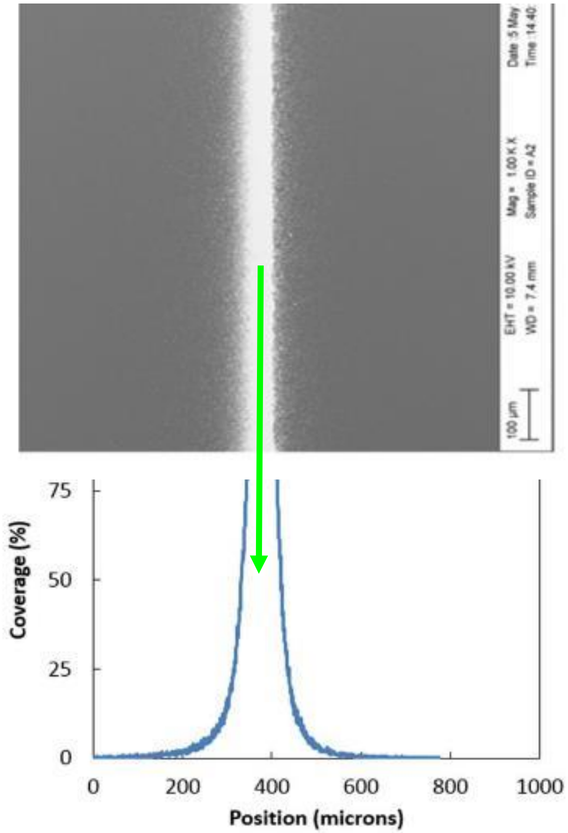




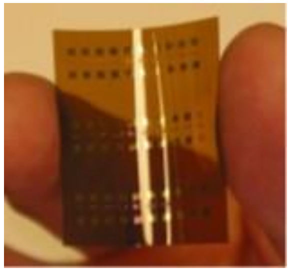
Project P.I. information available upon request.

Aerosol Jet 3D Printing of High Resolution Conductive traces

Project P.I. information available upon request.

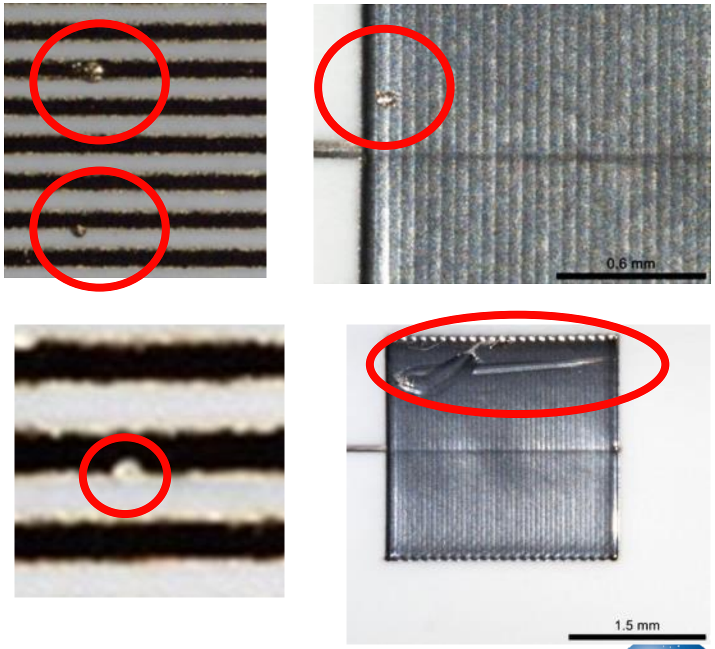


Process Overspray analysis (parametric study to improve upon several process variables)



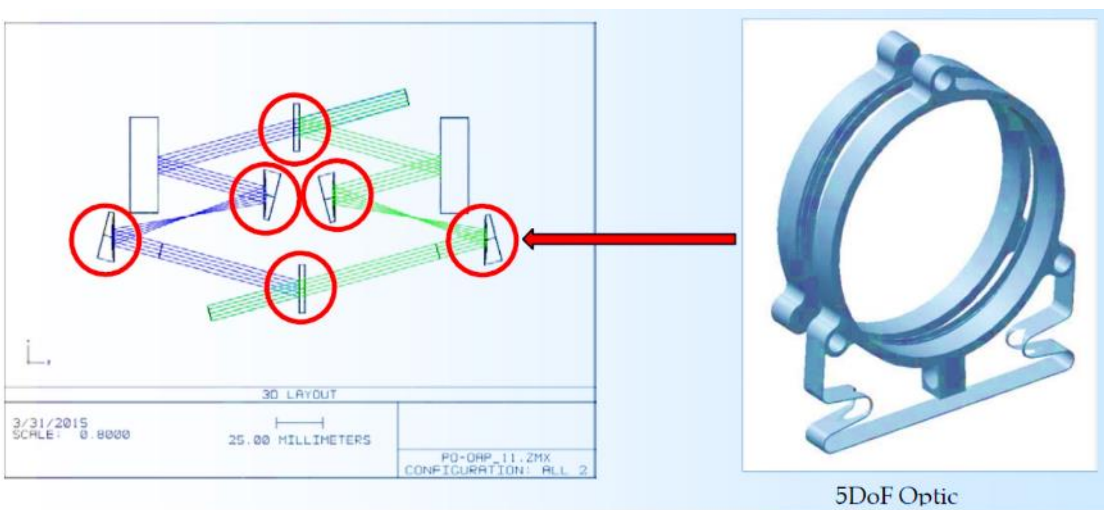
Aerosol Jet Printed Traces on Flexible Surface (Optomec)

Known flaw types



3D Printed Invar ® Coronagraph Bench

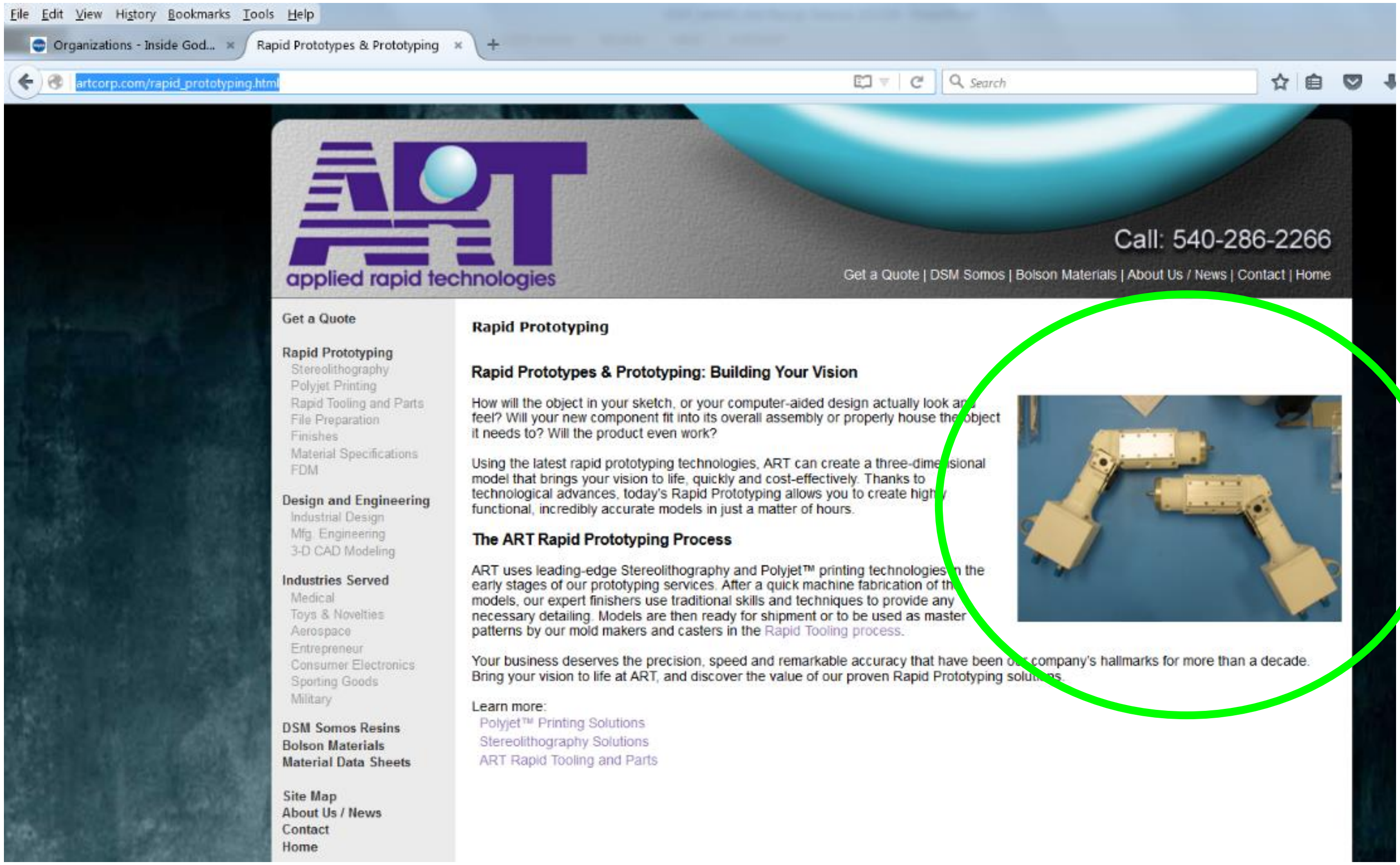
Project P.I. information available upon request.



- Compact Optical Assembly (COA) and optics standoffs for the Next Generation Visible Nulling Coronagraph (NG-VNC) ETU.
- Improves dimensional stability by eliminating mechanically fastened interfaces, thereby ensuring the bench achieves its residual stability requirement.
- Laser Powder Bed Fusion

Prototype AM tools for the Satellite Servicing Capabilities Office (SSCO)

Project P.I. information available upon request.



3D Printed PEKK for ATLAS Telescope Fiber Optic Routing

Project P.I. information available upon request.

FDM by Stratasys

3D printed, Carbon doped PEKK developed for high temperature extreme, high static dissipative electronics applications.

3D Printed Ultem 9085 for ATLAS Telescope cable clamping

Project P.I. information available upon request.

FDM by Stratasys

3D printed, low outgassing Ultem 9085 developed to replace metallic cable fasteners near critical detectors and sensitive hardware

Further Traction for AM-related Activities*

- GSFC Additive Manufacturing Working Group (Viens/300)
  - A GSFC working group for AM was initiated and has helped to bring individuals across the Center involved in AM in contact so there is a vehicle of sharing ideas and a known set of personnel that might be used as a resource in the further utilization of AM.
  - Several field trips to local AM facilities were conducted.

- NASA Additive Manufacturing Community of Practice was established on the NASA Engineering Network. The CoP has gained limited traction as yet but contributors are actively soliciting additional participation from across the agency.

- Code 100 participating as NASA Rep in America Makes (Ted Swanson)

- MUSTANG is an in-house effort to standardize spacecraft avionics packaging. Has been used on two separate missions (GEDI, PACE OCI) and uses AM to produce various parts using nylon, carbon fiber, Kevlar, magnetic materials, etc. AM parts are compared to traditional machined parts. (Robert Gheen)

- IPO Office has submitted SBIR topics on AM (Ericsson, Smith)

- The Cross Cutting Technologies Office has Identified AM as Technical Thrust area moving forward (Johnson, 500)

**GSFC AM Notes courtesy of M. Viens/300*